COLOR PERCEPTION

The physical stimulus that causes a color perception can be measured by straightforward physical methods, but predicting the perceived color is much more complex.

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To understand the physics of color, one must first understand the basics of color perception. Color is, first and foremost, a perception. Even though the stimulus that enters our eyes and produces the perception can be described and measured in physical terms, the actual color that we perceive is the result of a complex series of processes in the human visual system. Isaac Newton expressed this clearly in his famous treatise *Opticks* when he said:[1]

> If at any time I speak of light and rays as colored or endued with colors, I would be understood to speak not philosophically and properly, but grossly, and according to such perceptions as vulgar people in seeing all these experiments would be apt to frame. For the rays, to speak properly, are not colored. In them is nothing else than a certain power and disposition to stir up a sensation of this or that color.

This article outlines the human visual system and discusses the factors that influence the perception of color. It describes methods of specifying color perception systematically and then briefly describes how one transforms physical measurements of color stimuli into psychophysical color specifications.

Definitions of color

The word "color" is used with many different meanings. The two most common are "perceived color" and what the International Commission on Illumination calls "psychophysical color." (The CIE, known by the abbreviation of its French title, is an organization devoted to international cooperation on the science and art of lighting and is generally recognized as the leading authority on colorimetry.)

Perceived color is defined as the aspect of a visual perceptual phenomenon—distinct from form, shape, size, position, gloss or texture—that enables a person to distinguish between elements of the visual field and to characterize the elements by color names such as white, black, yellow, red, blue, green, gray, brown, orange, pink, purple and so on.

Psychophysical color is defined as a characteristic of visible radiation by which an observer may distinguish

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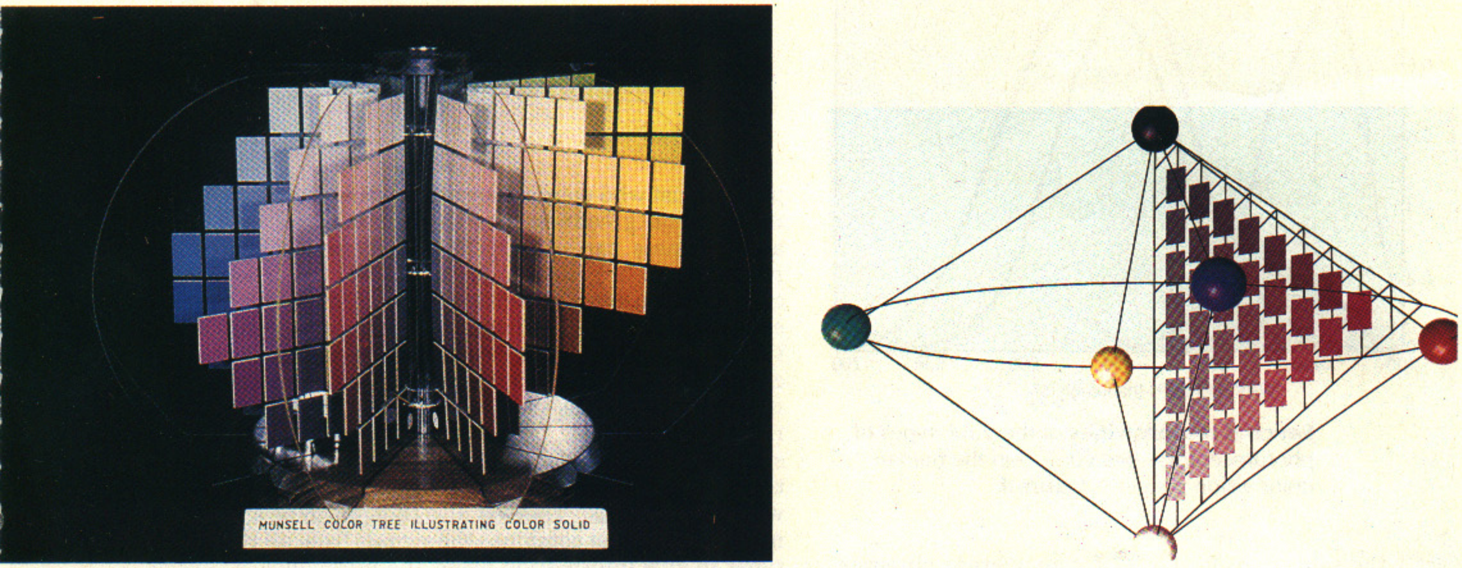


Geometrical arrangements of two well-known three-dimensional systems for classifying perceived colors. The Munsell color system (left) describes colors according to hue, chroma and value (lightness). The Natural Color System (right) classifies colors based on their resemblance to six "elementary" colors: white, black, red, yellow, green and blue. A distribution of violet-like colors in the NCS is depicted. **Figure 1**

such differences between fields of view of the same shape, size, position and structure as may be caused by differences in the spectral composition of the radiation. Psychophysical color is usually specified in terms of operationally defined quantities such as the "tristimulus values" discussed later in this article.

A third use of the word "color" is to describe a characteristic of an object. Strictly speaking, this use is a shorthand way of describing the psychophysical color of the radiation emitted, reflected or transmitted by the object.

A fourth use, at least in everyday speech, is to denote a dye or pigment that imparts color to an otherwise colorless material. The accepted technical word in this case is "colorant."

In all these cases, colors can be arranged in an ordered three-dimensional space. Figure 1 shows two examples of such spaces for object colors.

A color stimulus is electromagnetic radiation that can be characterized by a psychophysical color specification and that produces a perceived color on entering the human eye. There are many different ways of producing color stimuli. These include various types of light sources, either alone or combined with transmitting or reflecting materials containing mixtures of colorants. The physical details are beyond the scope of this article. We will simply accept that each element of an image, however it is produced, can be represented as a spectral radiance distribution—radiant power leaving the element per unit area per unit solid angle as a function of wavelength. An element will be taken to be the smallest component of an image that can be distinguished visually, even though in the physical sense the visual element may be produced by spatial or temporal integration of smaller elements such as the phosphor dots on a television screen.

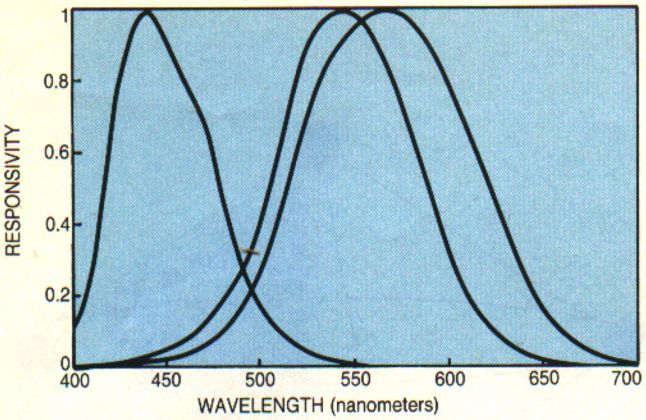
Human color vision system

When light enters the eye, it is focused onto the retina, absorbed by photoreceptors and converted into neural signals. Three types of photoreceptors—known as cones because of their shape—are sensitive to color. The rods, a fourth type of receptor, are active at low light levels but do not contribute to color vision. Each of the three types of cones has a different spectral responsivity, the general form of which is now fairly well known as a result of microspectrophotometry of excised retinas, reflection densitometry of living eyes and psychophysical studies of normal and color-defective observers.[2] Figure 2 shows the spectral responses for each. The three types of cones have sometimes been referred to as blue, green and red, but this is misleading because the peaks of the responses do not correspond to wavelengths that are usually perceived as having those colors. For example, the long-wavelength response peaks at about 570 nm, a wavelength that usually has a yellow appearance.

The three responses have considerable overlap, a feature that is necessary to allow the visual system to distinguish light of different wavelengths. If, for example, wavelengths in the range 540–570 nm excited only one of the three cone types, the visual system could not distinguish between intensity differences and wavelength differences in this range. In practice all wavelengths in the range excite both the long- and the middle-wavelength cones, but the ratio of the two responses varies with wavelength, allowing the observer to perceive a range of colors from green to yellow.

A fundamental consequence of the existence of only three types of photoreceptors is that many different spectral radiance distributions can produce the same perceived color. For example, approximately 6 watts of 540-nm radiation mixed with approximately 25 watts of 650-nm radiation will have the same effect on the three cone types as approximately 10 watts of 580-nm radiation. Thus no matter what subsequent processing the visual system applies to the signals from the three cone types, it cannot distinguish between the two stimuli.

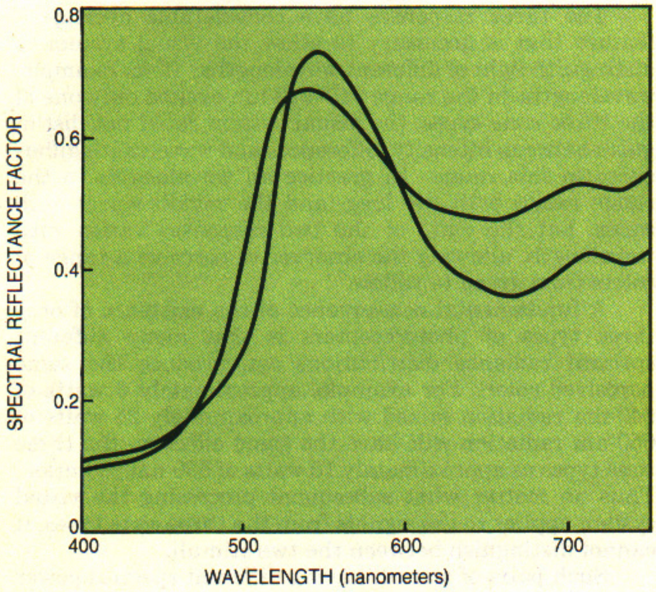
Such pairs of stimuli having different spectral power distributions but producing (other things being equal) the same perceived color are known as metamers. Figure 3 shows a more complicated example. Here we see the spectral reflectance curves of two paints. When illuminated by average daylight, the spectral radiance distributions reflected by these paints are different but produce exactly the same absorptions in the three cone types and thus



Spectral responsivities of the three types of photoreceptors—the cones—in the human color vision system. **Figure 2**

exactly the same perceived color for an average observer. Of course, if the illuminating source is different from average daylight, the reflected spectral power distributions may no longer produce a color match. Similarly, if the observer has cone sensitivities different from the average, there may not be a color match even under average daylight. Because almost all color reproduction techniques, whether printing, photography, television or any other method, produce metameric matches to the original, these matches will be sensitive to changes of illuminant or observer.

Once they are produced by the three cone types, the neural signals are subject to a great deal of processing by the rest of the visual system. It is generally believed that the first stage after the cones includes two "opponent" channels, one known as the red–green channel and the other as the yellow–blue channel. Our belief in the existence of these channels is linked to the opponent-process theory of Ewald Hering, a 19th-century German physiologist who pointed out that neither the attributes of redness and greenness nor the attributes of yellowness and blueness can coexist in a perceived color.[3] Thus redness and greenness, for example, are thought to correspond to opposite senses of signals in the same neural cells. Various "wiring diagrams" have been suggested for the relation between the cone signals and the opponent channels. All of them show the long- and medium-wavelength cones as the two major opposing inputs to the red–green channel. For the yellow–blue channel, the signals from the long- and medium-wavelength cones are thought to combine to oppose the signal from the short-wavelength cones. There is also thought to be a nonopponent channel that combines the signals from all three cone types to give information about the luminance, a psychophysical quantity that measures the intensity per unit area of light in a stimulus.



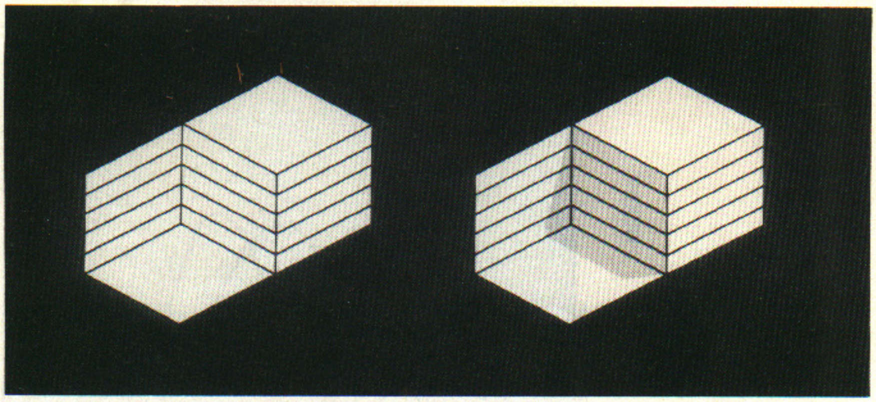
Spectral reflectance factors of a metameric pair of paints. When the two paints with these spectral reflectance factors are illuminated by average daylight, they have the same perceived color, despite their physical differences. **Figure 3**

Adaptation

So far we have discussed color stimuli and perceived colors as if they occurred in isolation—that is, as a uniform field of color on a black background. While this is often a very useful standard stimulus configuration for fundamental studies of color phenomena, it hardly corresponds to the real world of complicated scenes and complicated images. In practice there is no one-to-one relationship between a color stimulus and a perceived color. The perceived color is determined not only by the color stimulus to which it is directly associated but also by the state of adaptation of the visual system, by neighboring stimuli in the field of view and by other physical, physiological and psychological factors.

Color can occur in several modes of appearance, the four most important ones being the aperture mode, the object mode, the illumination mode and the illuminant mode.[4,5] The aperture mode is the one we have dealt with so far—where the stimulus is seen simply as light surrounded by darkness. In the object mode, we see the stimulus as emanating from an object illuminated by a light source. In the illumination mode, we see light as pervading a whole scene and illuminating objects, whether or not the actual source of the light can be seen. In the illuminant mode, we see the stimulus as a source of light. This last mode, which is sometimes called the self-luminous mode, includes stimuli in a complex field that are very much brighter than the other stimuli. It does not include stimuli that are known to be light sources but whose brightness is at or below the overall brightness of the scene so that they appear to be in the object mode. Examples of such "pseudo-object colors" are some indicator lights and, under certain conditions, the colors on a self-luminous video display.

The human visual system has a remarkable ability to adapt to changes in the quantity and quality of illumination. A piece of white paper will generally appear white both in bright daylight and in an average office even though the amount of light reflected may be 100 times more in daylight. In fact the amount of light reflected from a dark gray sheet of paper in daylight is much more than that reflected from a white sheet in a windowless office. The visual system also adapts to overall changes of color; for example, we are often unaware that daylight is very much bluer, in the physical sense, than incandescent



Thiéry's figure (left) and a modified version (right) in which the shaded portion may be perceived as a shadow or as a painted area depending on the perceived form of the figure as a whole. (Courtesy of Lawrence Arend, Eye Research Institute, Boston, and Mark Fairchild, Rochester Institute of Technology.) **Figure 4**

lamps or most fluorescent lamps.

The color stimulus reaching the eye is the product of the spectral power distribution of the illuminant and the spectral-reflectance-factor distribution of the object. The visual system reduces this stimulus to three signals and then, by complicated processing involving the three signals from each other element of the visual field, attempts to discount the effect of the illuminant and to create a perceived color that represents the object and not the illuminant. This process is known as chromatic adaptation. It succeeds to a remarkable extent, but not perfectly.

One example showing the marked dependence of perceived color on the surrounding stimuli is a stimulus that appears yellowish orange when seen in isolation. The same stimulus will appear brown when seen against a much brighter white background. In fact brown is one of several perceived colors that can occur only in the object mode. Other such colors include gray and olive.

Perceived color, and particularly the mode of appearance, may also be affected by higher levels of processing in the brain, including memory of the customary appearance of scenes and assumptions about the context in which stimuli are perceived. Such effects of an observer's knowledge or assumptions about scene content are known as cognitive effects. Figure 4 shows an interesting example. On the left-hand side is Thiéry's figure, a well-known illusion in which sometimes the lower left and sometimes the upper right portion of the figure is perceived as a cube with a corner pointing toward the observer. For many observers, the perception switches back and forth between the two possibilities. On the right-hand side is a more complex version, suggested by Lawrence Arend of the Eye Research Institute in Boston and developed by Mark Fairchild of the Rochester Institute of Technology. In this version a shaded area has been added that is perceived either as a painted area or as a shadow on a uniformly colored surface, depending on the perception of the figure as a whole.

Color names and color-order systems

When people are asked to describe a perceived color, they generally resort to the use of color names. These may be names based on well-known objects, such as coral, lilac, olive and chocolate, or they may be basic names presumably learned in childhood. One commonly held theory is that there are precisely 11 basic color terms: white, black, red, green, yellow, blue, brown, gray, orange, purple and pink.[6] In addition, there are many other color names ranging from the mundane to the exotic, together with qualifiers such as dark, light and dull, and combinations such as reddish purple or grayish blue.

For scientific purposes a random collection of names is much less useful than an ordered system. There are several alternative principles by which one can organize and analyze perceived colors. Ralph Evans has suggested that there are five perceptual variables, which he calls hue, saturation, lightness, brightness and brilliance.[4] For nonfluorescent object colors, these variables are generally reduced to three: hue, saturation and lightness. The use of three basic attributes is related to the fact that there are three types of photoreceptors to respond to a single color stimulus, but it ignores the possible effects of other stimuli in the field of view.

Hue is the attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors red, yellow, green or blue or to a combination of two of them. Saturation is but one of several different terms, each with its own definition, that have been used to refer to the degree to which a perceived color differs from achromatic—white, gray or black. Others include chroma, chromatic amount, chromatic content, chromaticness, colorfulness and vividness. Lightness is the attribute describing whether an object color appears lighter or darker than another under the same illuminating and viewing conditions. It measures whether the object appears to reflect a greater or smaller fraction of the incident light.

The best-known example of a color-order system based on this type of classification is the Munsell system, which describes colors in terms of hue, chroma and value (lightness). The system is defined in psychophysical terms and illustrated by paint chips designed to be viewed under a standard daylight illuminant against a gray background.

An alternative method of classification of perceived colors is based on their degree of resemblance to six "elementary" colors: white, black, red, yellow, green and blue. All other colors can be described in terms of their resemblance to these six. Since any given color can resemble at the most two of the chromatic elementary colors (red, yellow, green and blue), and since the total of the resemblances is taken by convention to equal 100%, there are only three independent scales in this classification. As before, this is not surprising in a system that describes a single color stimulus. The best-known example of this type of classification is the Natural Color System. Unlike the Munsell system, the definition of the NCS is strictly conceptual. Sets of painted chips with psychophysical specifications are available to illustrate the system but do not define it.

Figure 1 shows the geometrical arrangements of the Munsell system and the NCS. In the Munsell system, all colors of a given lightness lie on one horizontal plane. For each hue there is a theoretical maximum to the chroma, but the maximum occurs at a different lightness level for each hue. Consequently the limits of the Munsell system are irregular in shape. In the NCS, samples with the theoretical maximum chromaticness are all plotted at the same horizontal level, giving a much more symmetrical appearance. However, this means that surfaces of equal lightness have very irregular shapes in the NCS.

Color is defined as being distinct from form, shape, size, position, gloss or texture—a useful distinction when we attempt to analyze and bring order to our perceptions and to the physical and psychophysical specification of stimuli. However, the geometrical and spectral attributes of appearance are often difficult to separate, and a full description of appearance must include consideration of the geometrical attributes. Attributes in this class include gloss, haze, translucence, luster and texture, but they are beyond the scope of this article.[7]

Specification of psychophysical color

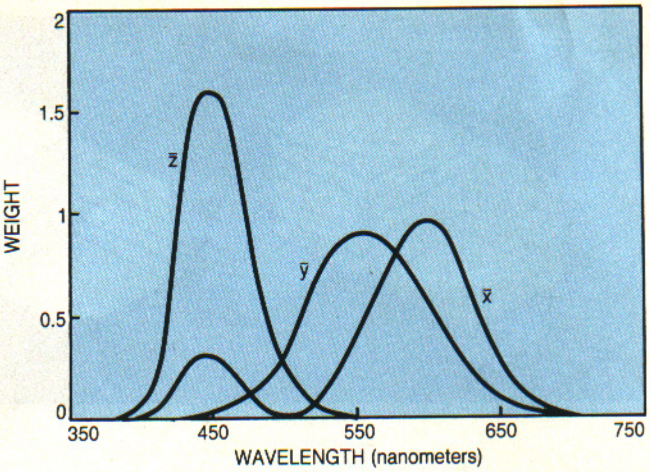
The full physical specification of a color stimulus is multidimensional (there is a radiance at each wavelength in the visible spectrum), but because the perceived color of an isolated stimulus is only three dimensional, one needs an operational definition of psychophysical color such that all stimuli that are metameric to one another have the same three-dimensional specification. Ideally such a specification would be based directly on the absorption characteristics of the three types of cones. In practice, however, these characteristics, although better known than they were a few years ago, are still not known sufficiently well for this purpose. Consequently psychophysical color specifications are based on a system known as the CIE 1931 Standard Observer.[7] This consists of three weighting functions—$\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ (see figure 5)—that are known as color-matching functions and are used to calculate three "tristimulus values"—X, Y and Z—according to the following equations:

$$X = k\int L(\lambda)\,\bar{x}(\lambda)\,\mathrm{d}\lambda$$

$$Y = k\int L(\lambda)\,\bar{y}(\lambda)\,\mathrm{d}\lambda$$

$$Z = k\int L(\lambda)\,\bar{z}(\lambda)\,\mathrm{d}\lambda$$

Here λ is the wavelength, $L(\lambda)$ the color stimulus function (radiance as a function of wavelength) and k a normalizing constant. The limits of integration are the limits of the visible spectrum and are typically 380 and 780 nm. The system is based on the average color-matching characteristics of many observers and on assumptions of linearity and additivity. For most practical purposes the assumptions hold and the system works well, although it is known to break down in certain extreme situations.[7] The color-matching functions of real observers are scattered about the average, but the use of an average observer as a standard has immense practical advantages in color specification.



Color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ of the CIE 1931 Standard Observer. **Figure 5**

A useful feature of the system is that $\bar{y}(\lambda)$ was chosen so that the Y tristimulus value is proportional to the luminance.

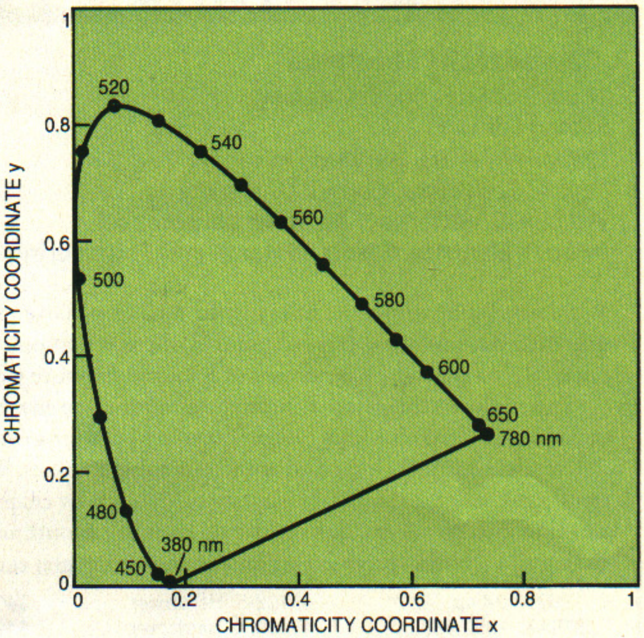
It is often convenient to calculate two other quantities, x and y, called chromaticity coordinates:

$$x = X/(X + Y + Z)$$
$$y = Y/(X + Y + Z)$$

Psychophysical color can then be specified as (Y,x,y), with Y representing the quantity of light in the stimulus, and x and y representing the chromatic quality of the stimulus. The diagram formed by plotting x and y in rectangular coordinates is known as the CIE 1931 chromaticity diagram. When monochromatic lights are plotted in this diagram they form a roughly horseshoe-shaped curve known as the spectrum locus (figure 6). The line joining the ends of the spectrum locus is known as the purple boundary. All real colors lie within the area enclosed by the spectrum locus and the purple boundary.

As mentioned above, the purpose of the CIE system is to provide a means of specifying psychophysical color in such a way that metamerically matching stimuli have the same specification. The system is not intended to specify appearance, although if all other conditions are equal a one-to-one correspondence exists between the psychophysical specification and the perceived color. Because of this one-to-one correspondence, the CIE system is sometimes used to specify appearance. However, this use is misleading. Remember, for example, that there is a nonlinear relationship between the psychophysical quantity luminance and the perceived brightness and that this relationship depends strongly on the spatial and temporal properties of the stimulus and its surroundings.

Furthermore, perceived colors are not represented in a very uniform way in CIE tristimulus space or in the CIE chromaticity diagram. In particular, equal distances do not by any means represent equally perceptible differences in perceived color. Consequently many formulas have been developed to calculate the sizes of perceived color differences from pairs of tristimulus values. These formulas leave much to be desired for use in predicting appearance, and especially in comparing appearances under different adaptation conditions or, equivalently, conditions with different white points. (The white point is



Chromaticity diagram of the CIE 1931 Standard Observer. All real colors lie within the area enclosed by the spectrum locus (horseshoe-shaped curve) and the purple boundary (straight line). **Figure 6**

the stimulus the viewer perceives as white in a given setting.) In recent years, therefore, color scientists have devoted much work to developing more sophisticated color appearance models. Yoshinobu Nayatani and his coworkers in Japan[8] and Robert Hunt[9] in Great Britain have developed two of the best known of these models.

Appearance matching

The ultimate aim in color image reproduction is to match the appearances of the original and the reproduced images. An intermediate step often involves matching the appearances of images produced in different media, such as reflection prints and self-luminous video displays. Exact physical matching is usually impossible, for a number of reasons. First, wavelength-by-wavelength reproduction of the stimuli cannot be achieved in most systems because the number of primaries (dyes, inks, phosphors and so on) is limited, often to only three. Second, the dynamic range from the darkest to the lightest reproducible stimulus is different from—usually less than—that in the original image. Third, the "gamut"—the range of reproducible chromaticities—is different from system to system, so one must develop algorithms for reducing the gamut of the original image without unduly distorting the overall appearance of the reproduction.

Hunt has identified six types of color reproduction:[10]

▷ *Spectral* color reproduction is the equality of spectral reflectance factors or relative spectral radiances.

▷ *Colorimetric* color reproduction is the equality of chromaticities and relative luminances.

▷ *Exact* color reproduction is the equality of chromaticities and absolute luminances.

▷ *Equivalent* color reproduction is the equality of appearance.

▷ *Corresponding* color reproduction is the equality of appearance when the original and reproduction luminance levels are the same.

▷ *Preferred* color reproduction allows departures from equality of appearance to achieve a more pleasing result.

Additional problems arise in matching a self-luminous display with a transparency or a reflection print, because the clues that enable the visual system to assess the color of the illuminant are different in each, which may lead to different degrees of adaptation. With reflection prints, and to a lesser extent transparencies, direct clues result from a real illuminant, which may be assessed via reflected highlights, for example. For self-luminous displays, the scene illuminant does not exist physically but must still be estimated in some way by the visual system. Clues received from reflected highlights on the face of the display may be misleading because they depend on the ambient illumination rather than the scene itself. Another important factor, also related to the visual system's ability to assess the illuminant, or white point, is the nature of the surrounding region. A change from a white to a black surrounding region, for example, can make a very big difference in the appearance of an image.

Yet another factor to bear in mind in cross-media appearance matching is metamerism. The primaries in different systems usually have different spectra, so even when the CIE tristimulus values are equated, the match is metameric and may not hold if the illuminant is changed or if a real observer's color-matching functions differ from the standard.

Color perception is a fascinating but complex subject involving physics, physiology, photochemistry and psychology. An article of this length can do no more than present an outline and introduction to the subject, and the reader desiring more details should consult the references. They have been chosen to cover many different aspects of color science but with an emphasis on a physicist's point of view.

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